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Cortical Control of Neural Prostheses

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Abstract

Experiments using multichannel, chronic neural recordings in awake, behaving animals are proceeding which show the potential of controlling electromechanical devices directly using signals recorded from the motor cortex. We have found the preferred direction of at least some motor cortical units to be relatively consistent over a 2½ month period. We continued to develop recording electrode arrays for use in rhesus monkeys. We also developed a guinea pig preparation that is useful for evaluating new electrode designs and investigating the recording stability of the implants. The guinea pig implants have resulted in 30-50 units being recorded from 33 channels on a daily basis. Finally, we continued to refine an algorithm to control a modeled robotic arm using arm end-point trajectories that can be estimated with the instantaneous population vector recorded from a set of motor cortical units.

Work Performed During Reporting Period

1. Evaluation of Implantable Cortical Recording Electrodes

In the previous project periods, we used 16- and 32-channel arrays made of 50-micron diameter stainless-steel microwires (NB Labs, Dennison, Texas). These wires have blunt tips and a Teflon coating that extends the length of the electrode. Polyethylene glycol is used to cover the initial segments of the electrodes during the penetration. This sugar substance is dissolved with sterile saline prior to fixing the electrode in place with acrylic. The electrode connector is a miniature IC-type socket from Microtek. The 32-channel array consists of two 16-channel arrays attached at the connector and samples a cortical area approximately 2.5 mm by 2.5 mm.

In the current project period, we developed the techniques for making our own microelectrode arrays because of a desire to more closely control the electrode surface properties, array size and uniformity, and geometry of the electrode tips. This electrode system consists of an arbitrary rectangular array (typically 3 rows of 11 wires each) of tungsten microwires (50 mm total diameter, polyimide insulated; California Fine Wire Inc.). The wires are cut with sharp scissors to have blunt tips. Microtek connectors are used to interface with the buffer amplifiers. The electrodes are soaked in alcohol and ultrasonically cleaned in deionized water prior to being gas sterilized. We have found these electrodes very effective for recording unit activity (see results below).

To facilitate electrode evaluation, we have developed a chronic guinea pig preparation that involves essentially the same surgical and recording procedures as the monkey preparation. Many of the data reported in this section are from the guinea pig preparation. One of the interesting outcomes of these activities is that despite the procedural similarities, there seems to be significant differences in electrode performance in monkeys implants compared to guinea pig implants. We are continuing to explore this issue.

Unit Variability in Chronic Neural Recordings

As part of our ongoing activities, we are working to describe the variability in chronic neural recordings. Characterizing unit variability is a complicated process because the variability could be the result of several, largely independent factors, including differences in unit activity during the recording session and day-to-day differences in the electrode/neural interface that result from encapsulation or relative motion between the electrode and brain. For the present purpose, a well-isolated spike waveform that remains consistent over the time span of interest is defined as a "stable" unit. Similarly, a well-isolated spike waveform that occurs intermittently is defined as an "unstable" unit. Unit waveforms on a channel that cannot be clearly separated is defined as "multi-unit".

In this section, the general findings will be illustrated using a few days of recordings from a recent guinea pig implant (gp6). In this animal, we have recorded extensive unit activity for over a month using a 33-channel tungsten electrode implanted in somatosensory cortex (as of 30 October the implant is still working). Five-minute recordings were made daily while the animal was resting quietly. Within a single recording session, unit recordings range from well-isolated single units (Figure 1, left) to multiunit clusters (Figure 1, right). Multiunits were discriminated mainly through setting an amplitude threshold, while single units were discriminated through specific features of the waveform, such as amplitude, duration, and slope.

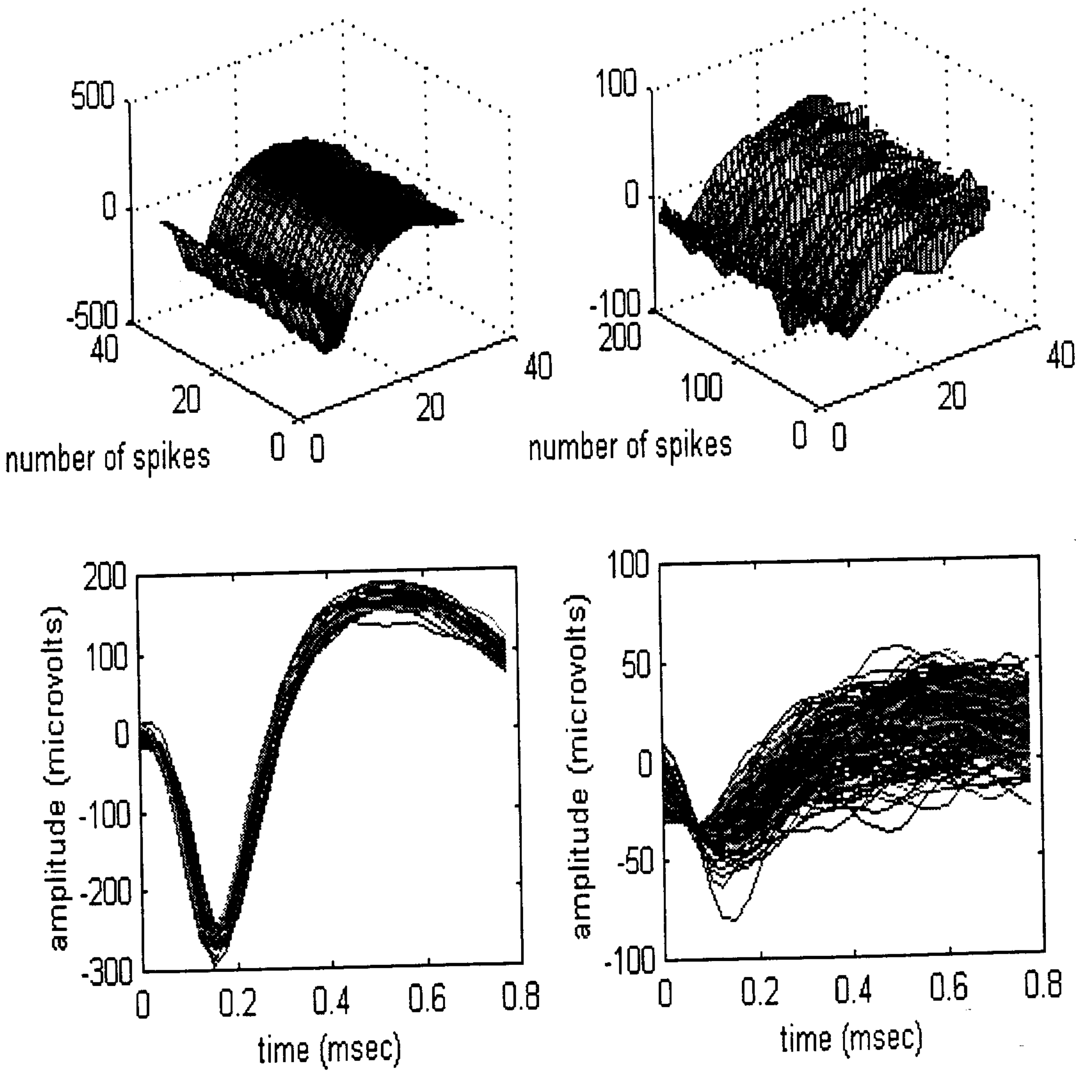

Figure 1. A single unit (left column) and multiunit (right column) recorded on two different channels on one day. (left, ch21; right, ch28; gp6, 090197)

On any given day, about 26 to 28 of the 32 channels (85%) exhibited unit activity (Figures 2-4). On any given channel, the unit activity was reliable, i.e. if the channel worked on one day then it tended to work on all other days.

Over the course of a two-week segment, some channels exhibited one or more stable units, while other channels exhibited unstable units or no unit activity. For example, a relatively large (75 μV) unit was recorded on channel 1 starting on post-op day 24 (Figure 3, channel 1, green trace) and it persisted for four days (Figure 4, channel 1, green trace). Also on post-op day 24, another unit (75 μV) was recorded on channel 4 (Figure 3, channel 4, green trace) that persisted for 8 days. It is as easy to find examples of unstable units. On post-op day 22, a large unit was recorded on channel 24 (Figure 2, channel 24, red trace), but it did not persist in the following days.

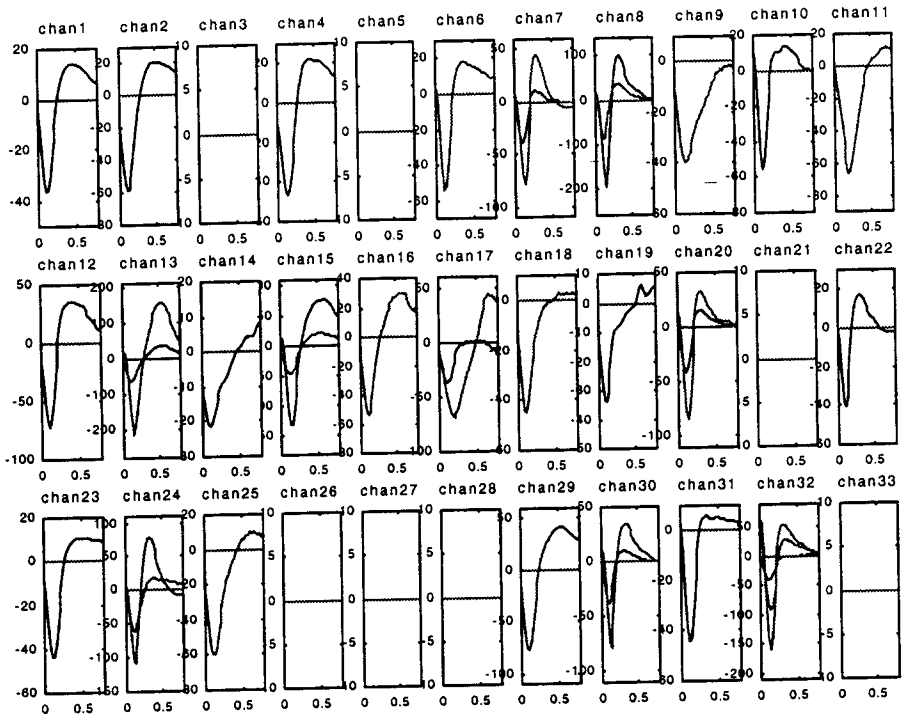

Figure 2. Averaged spike waveforms from animal gp6 on one day (post-op day 22). A total of 36 single units or multiunits were recorded on 28 of the 33 electrodes. The unit amplitudes range from about 40 μV to 200 μV. The spike waveforms that are shown were averaged from five minutes of recording while the animal was resting quietly. Each plot has units of time on the abscissa (0.8 ms width) and voltage on the ordinate (variable scale in μV). Each color trace represents a separate unit or multiunit for the corresponding channel as per the unit discrimination criteria described in the text. The horizontal line represents 0 μV. The layout of the 33 plots matches the physical layout of the electrode (3x11 array). The electrodes in each row are separated by about 250 μm and the rows are separated by about 500 μm. (gp6, 082697)

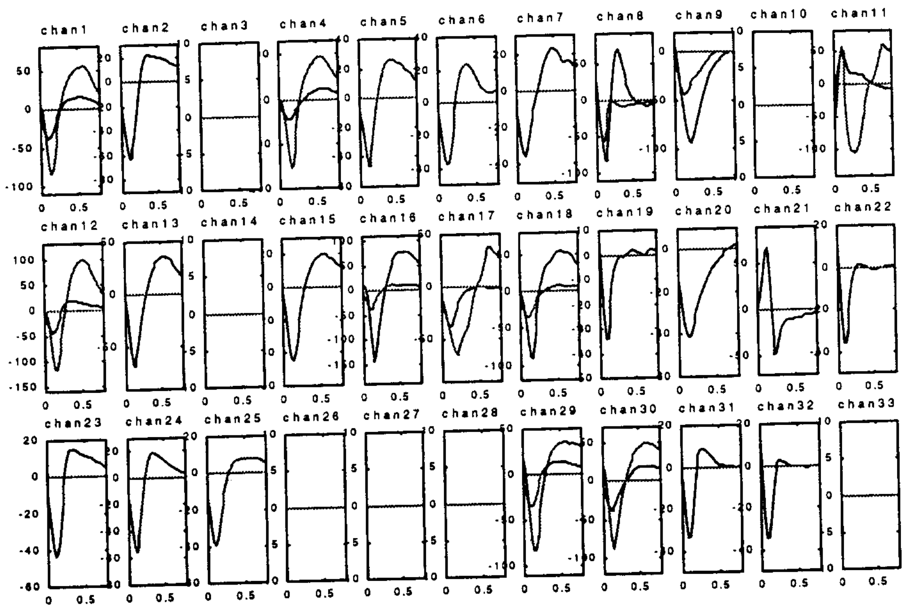

Figure 3. Averaged spike waveforms from animal gp6 on a second day (post-op day 24). A total of 37 single units or multiunits were recorded on 26 of the 33 electrodes. Same format as in Figure 1. (gp6, 082897)

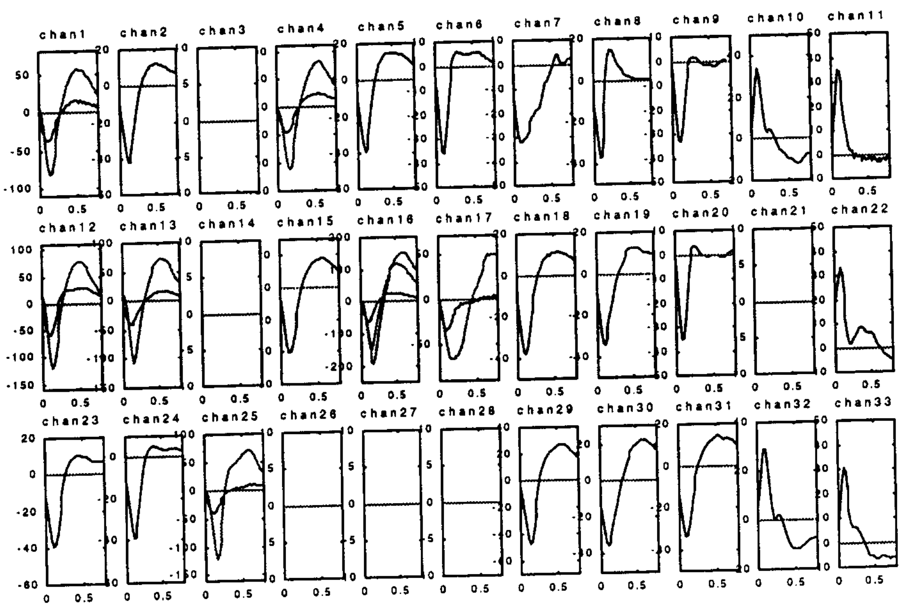

Figure 4. Averaged spike waveforms recorded from gp6 on a third day (post-op day 28). A total of 35 single units or multiunits were recorded on 27 of the 33 electrodes. Same format as in Figure 1. (gp6, 090197)

With some limitations, the spike activity of each unit is useful for characterizing unit variability. This is complicated by possible changes in spike statistics of a given unit from day-to-day—even under "spontaneous" conditions in an awake animal—but spike activity does provide another dimension for characterizing a unit. Along these lines, the average spike rates and inter-spike interval histograms were calculated for each recorded unit on the array for each day. Figures 5 and 6 provide examples of these plots for a single day; however, additional analysis is required to fully describe the daily trends.

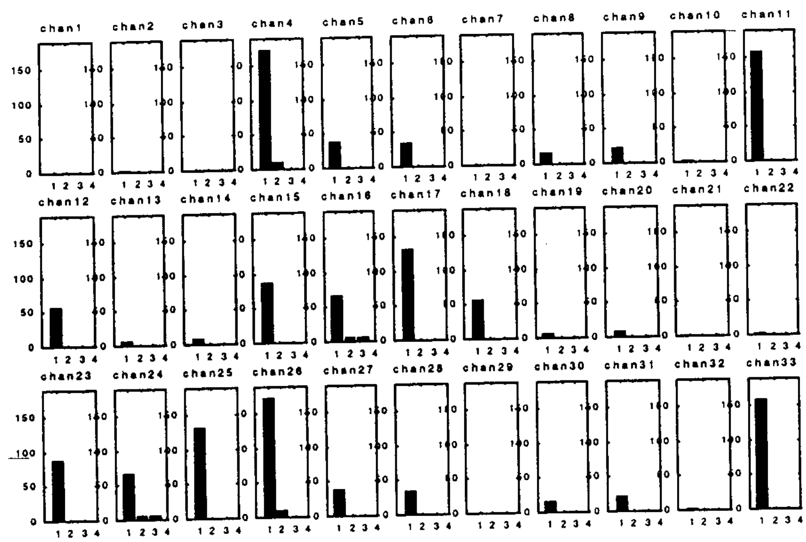

Figure 5. Average spike rates (spikes/second) for units recorded over five minutes on post-op day 28. The height of each bar in each plot illustrates the average spike rate of a unit on the associated channel. There are a maximum of four units per channel. (gp6, 090197).

While most of our electrode related activities to date have involved relatively standard microelectrodes consisting of microwire arrays, we are also actively working with external groups in the evaluation and development of alternative implantable multichannel microelectrodes. These electrode arrays contrast with our microwire arrays in four major respects: (1) different site densities, (2) fixed geometries, (3) different recording and dielectric materials, and (4) reduced tethering forces. We are working with a group at the University of Michigan (headed by Dr. David Anderson) to design and evaluate their 3-dimensional, silicon-based microelectrode system. We are also working with a group at the University of Utah / Advanced Bionic Systems (headed by Dr. Richard Normann) to incorporate their 3-D silicon electrode into our experimental preparation.

The University of Michigan group provided several "sham" 3D electrode arrays (full-size electrode without a ribbon cable or external connector) and their custom-made high-speed injection device. We found the implantation procedure for these electrode assemblies to be straightforward with few difficulties. We expect to receive delivery of working electrodes in the next reporting period. In October, one of the co-investigators (DRK) traveled to Ann Arbor and spent two days in Dr. Anderson's laboratory learning the UMich techniques. During the visit, we implanted several electrode assemblies in cat cortex.

2. Summary of Primate Neural Recordings

In this project period, we have continued to train monkeys to perform a 3-D reaching task while motor cortical unit activity is recorded. Table 1 summarizes the recording performance of the implants to date. A total of eight hemispheres in four monkeys have been implanted with the number of simultaneously recorded units ranging from a high to 27 units to a low of one unit.

Monkey	Electrodes	# Active Ch	# Cells	Amplitude
B-R	32	15	27	50-270
B-L	32	6	7	60-360
C-L	64	12	13	20-60
C-R	32	2	2	20-30
D-L	32	11	13	15-20
D-R	32	6	6	25-60
E-L	64	4	5	30-60
E-R	48	1	1	180

Table 1. Summary of Neural Recordings. Performance in the right (-R) and left (-L) hemispheres in animals B, C, D, and E are tabulated above. Monkeys B, C, and D have standard NB electrodes implanted in each hemisphere. Monkey E has revised electrode arrays. Left hemisphere E-L has a 32-channel tungsten microwire array, a revised NB Lab 16-channel array with increased electrode spacing, and a standard NB Labs 16-channel array. The right hemisphere E-R has a 16-channel tungsten array, a standard NB Lab 16-channel array, and a 16-channel NB Lab array that was coated with laminin by Dr. David Martin at the University of Michigan.

Stability of Preferred Direction

An important and interesting question is whether the preferred direction of a directionally-tuned unit varies significantly from day-to-day over an extended period of several months. The preferred direction is that direction in which the unit has its maximal firing rate. A related question is whether the degree of tuning varies significantly from day-to-day. The degree of tuning is typically expressed as the correlation coefficient (R^2) the unit's response pattern and a cosine tuning function.

As preliminary answers to these questions, we analyzed the responses of one unit in one animal over a 2½ month period. Figure 6A illustrates the trial-by-trial variation in preferred direction over a sequence of 70 trials recorded over a 2½ month period. The preferred direction variations are plotted as the cosine of the difference angle between the preferred direction of each trial and the average preferred direction for all of the trials. A value close to one would indicate little difference between the two angles and, thus, stability in the preferred direction. These data demonstrate trial-by-trial variations, but a consistent long-term preferred direction. Figure 6B illustrates the trial-by-trial variation in the degree of tuning (R^2) for the unit. There is a gradual decline in the degree of tuning over the recording period.

When multiple trials from the same recording session (day) were averaged, the variability in both preferred direction and R^2 significantly decreased (Figure 7). This indicates that the averaged day-to-day variability is less than the trial-by-trial variability. Figure 8 shows the weekly averaged preferred direction of a unit recorded in the same animal.

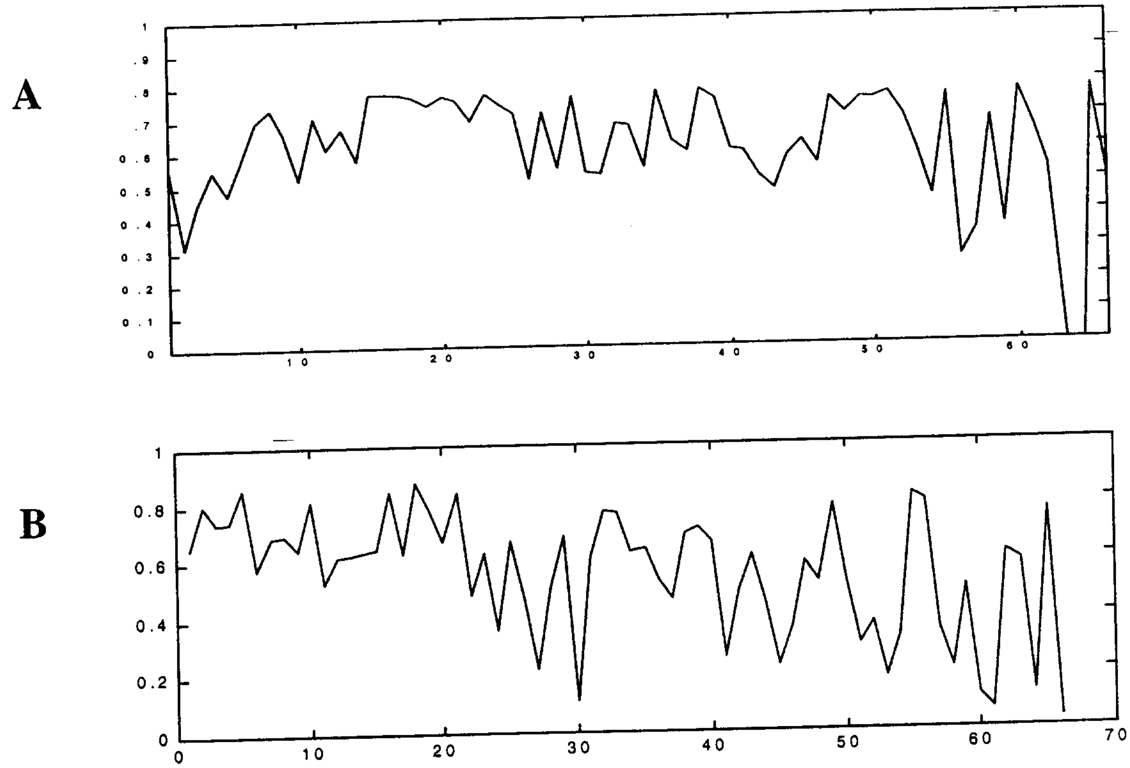

Figure 6. (A) Cosine of the difference angle between the preferred direction of each trial and the average preferred direction for all of the trials. (B) The degree of tuning expressed in terms of the correlation coefficient (R^2) between the unit response and a cosine tuning function.

A

B

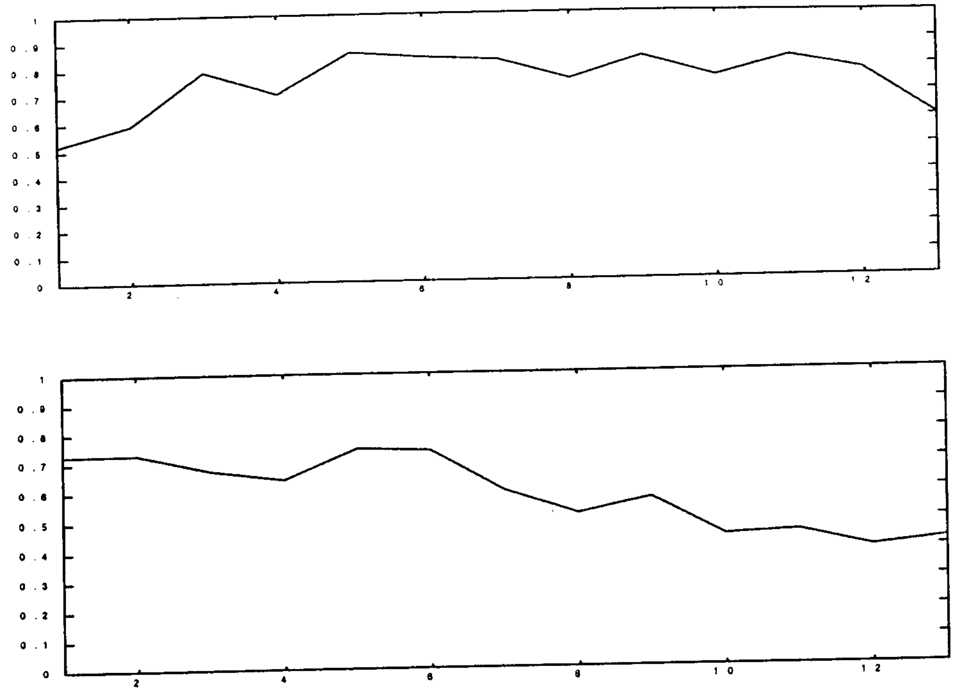

Figure 7. (A) Cosine of the difference angle between the averaged preferred direction for each recording session and the average preferred direction for all of the sessions. (B) The degree of tuning expressed in terms of the correlation coefficient (R^2) between the unit response and a cosine tuning function.

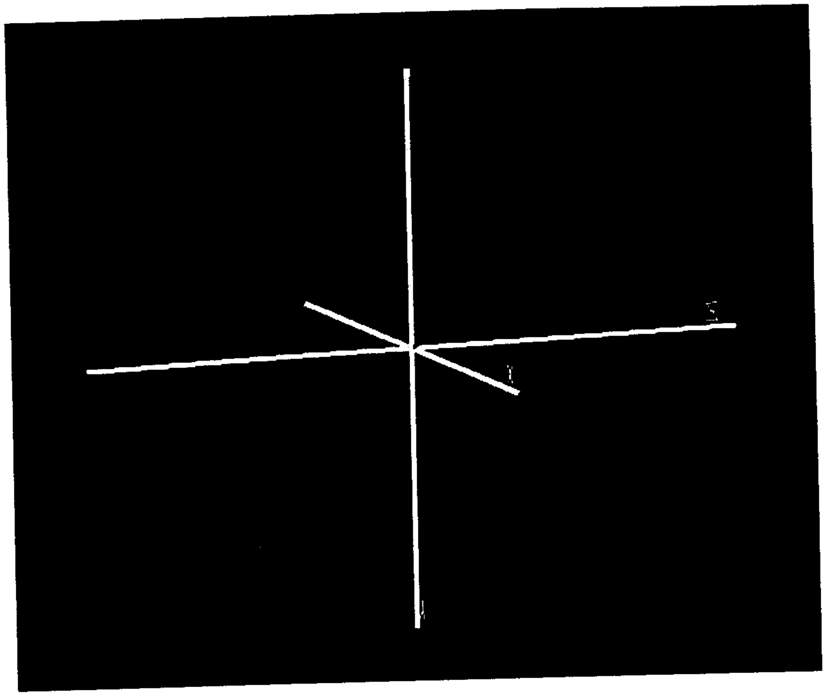

Figure 8. The preferred direction of DSP20 (left hemisphere implant) averaged weekly for the period of 4/23/97 through 7/9/97. All preferred direction were calculated from data sets with Monkey E performing the reaching task with the right arm.

Computer Simulation of Prosthetic Limb Movement

We have developed and implemented two algorithms controlling the robotic arm. One of these, the Berkinblit algorithm, was developed prior to the start of the contract. The other is a modified form of the pseudoinverse algorithm developed by Drs. Yamaguchi, Moran, and Si at ASU. During the reporting period, we have used the algorithm to control only the endpoint of a simulated anthrorobotic arm. Simply stated, the algorithm superposes the accelerations of the endpoint created by known moments and torques at the joints. The superposition is accomplished via the pseudoinverse of a nonsquare matrix, and simultaneously minimizes the joint effort required to accelerate the joints and the endpoint position error. As shown in Figure 9, the simulated (dashed line) and actual (solid line) endpoint trajectories are virtually identical. This indicates that we should be able to take a population vector developed from the motor cortical recordings and use it to move an anthrorobotic limb so that the endpoint moves consistent with the fingertip position.

The next step is to continue developing this algorithm so that not only the limb endpoint, but the joint trajectories chosen by the algorithm to move the endpoint, be made to look more like the actual anthropomorphic angles freely chosen by the monkey to perform the movement. As shown, only two (angles Q3 and Q4) of the three shoulder angles (Q1 to Q3), elbow angle (Q4), pronation/supination angle (Q5) and wrist angles (Q6 and Q7) of the simulation closely follow the angles chosen by the monkey to accomplish the endpoint motion.

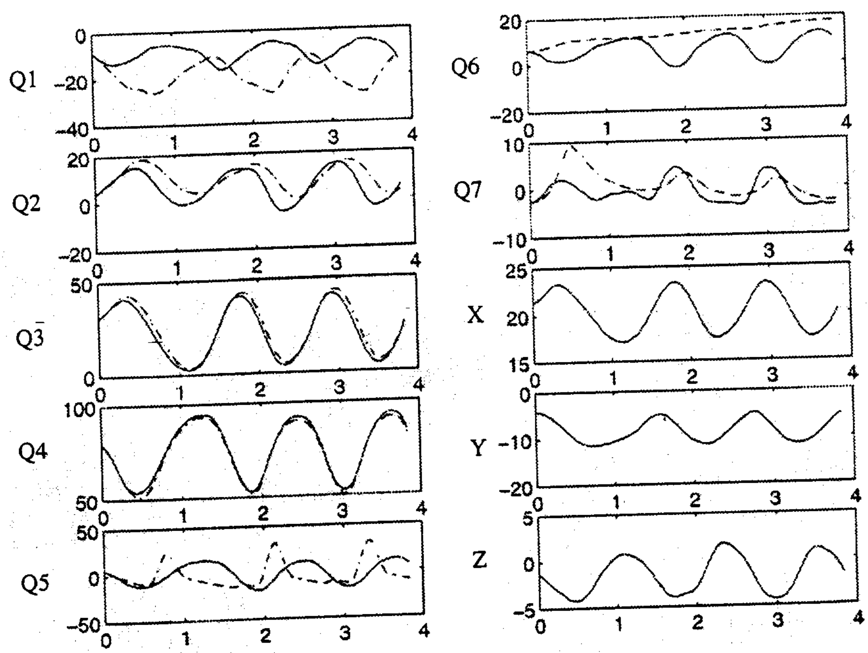

Figure 9. Comparison of simulated and actual joint angles (Q1-Q7) and end point positions (X,Y,Z) using the pseudoinverse control algorithm.

Work Anticipated for Next Reporting Period

Continued Development and Evaluation of Cortical Electrodes

We recently secured College funding to purchase equipment that will help in the characterization and fabrication of the microwire electrode arrays. This equipment includes a complex impedance meter that will allow for impedance spectroscopy. The general objective is to further characterize impedance fluctuations on each wire and relate it to recording performance and tissue reactivity. The equipment also includes a thin-film plasma depositer/etcher that will allow modification of the electrode surface, including controlled tip geometries.

In collaboration with the research groups at the University of Michigan and University of Utah, we expect to implant one or more animals (probably cats and/or guinea pigs) with the silicon-based microelectrodes.

Continued Cortical Implants and Behavioral Training in Rhesus Monkeys

We anticipate implanting one or more hemispheres in one or more monkeys to continue the progress in the core project areas.